Modeling and Evaluating Impact of Sub-Array MPPT

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Brief Overview

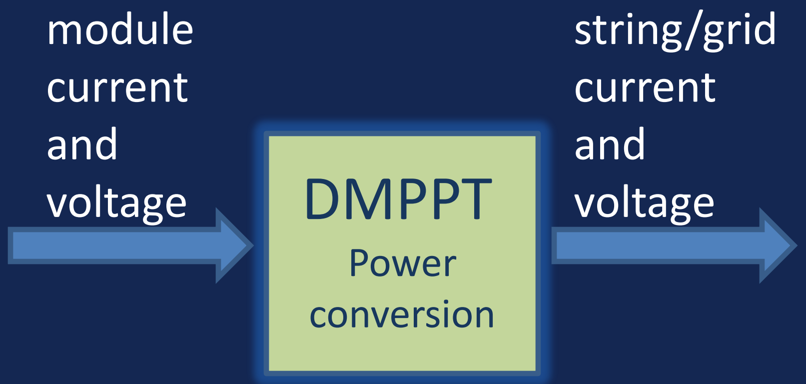
- Motivation
- Annual Simulation
- Impact of Sub-Array MPPT
- Applications to Performance Modeling

Problem: Photovoltaics and the Built Environment

- PV mismatch loss from:
  - Panel Variance
  - Soiling
  - Temperature
  - Solar Availability
    - Directional
    - Shading
- Mismatch = disproportionate losses!

Solution: Distributed Maximum Power Point Tracking (DMPPT)

- DC-DC converters or DC-AC microinverters which interface subset of PV array to the rest of the array or to the grid
- String, module, or bypass diode levels
- Many commercial products currently under development or available



GOAL

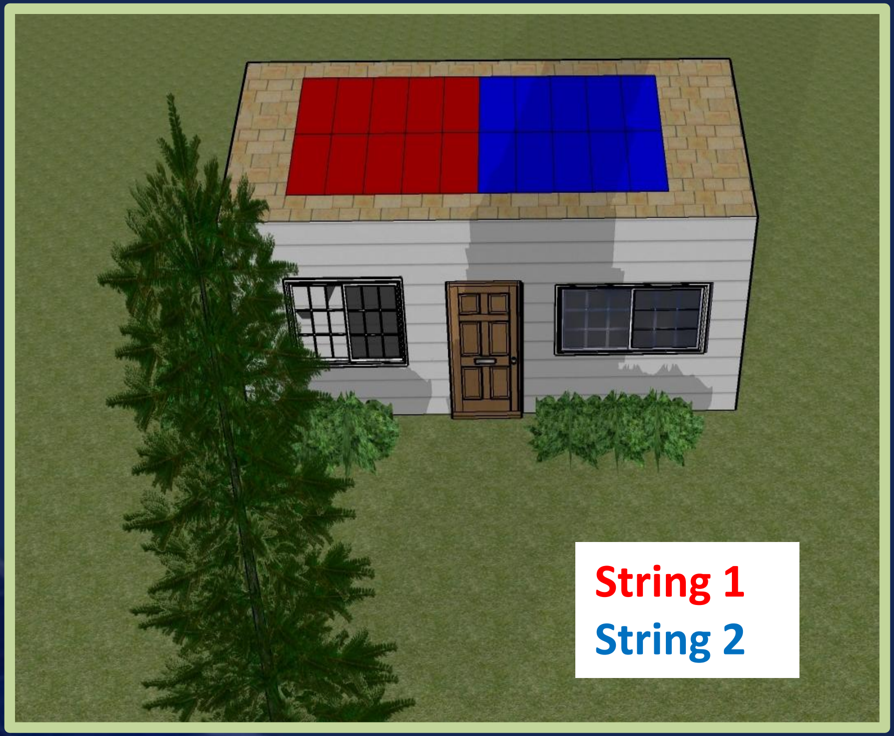
Methodology to accurately predict benefits of DMPPT

- What are qualities of PV systems that will benefit most?
- How should nonuniform operating conditions and DMPPT power converters be modeled?

Annual Simulation

- Simulation of annual array energy capture, shading loss, and power recovery potential
- MatLab models:
  - **Panel**: Shell 85W, cell level 5-parameter model (shaded and unshaded) with reverse breakdown
  - **Power Converters**: Prototype, efficiency based on detailed electrical models (~95% efficient on average) and measured insertion loss
  - **Inverter**: Solectria, efficiency based on manufacturer's curves using input voltage & DC power from the panels
- Weather data: TMY-3 hourly irradiance (HDKR) and temperature (NOCT) for Boulder, CO
- Experimental Validation: Simulation performance within 5% of test system

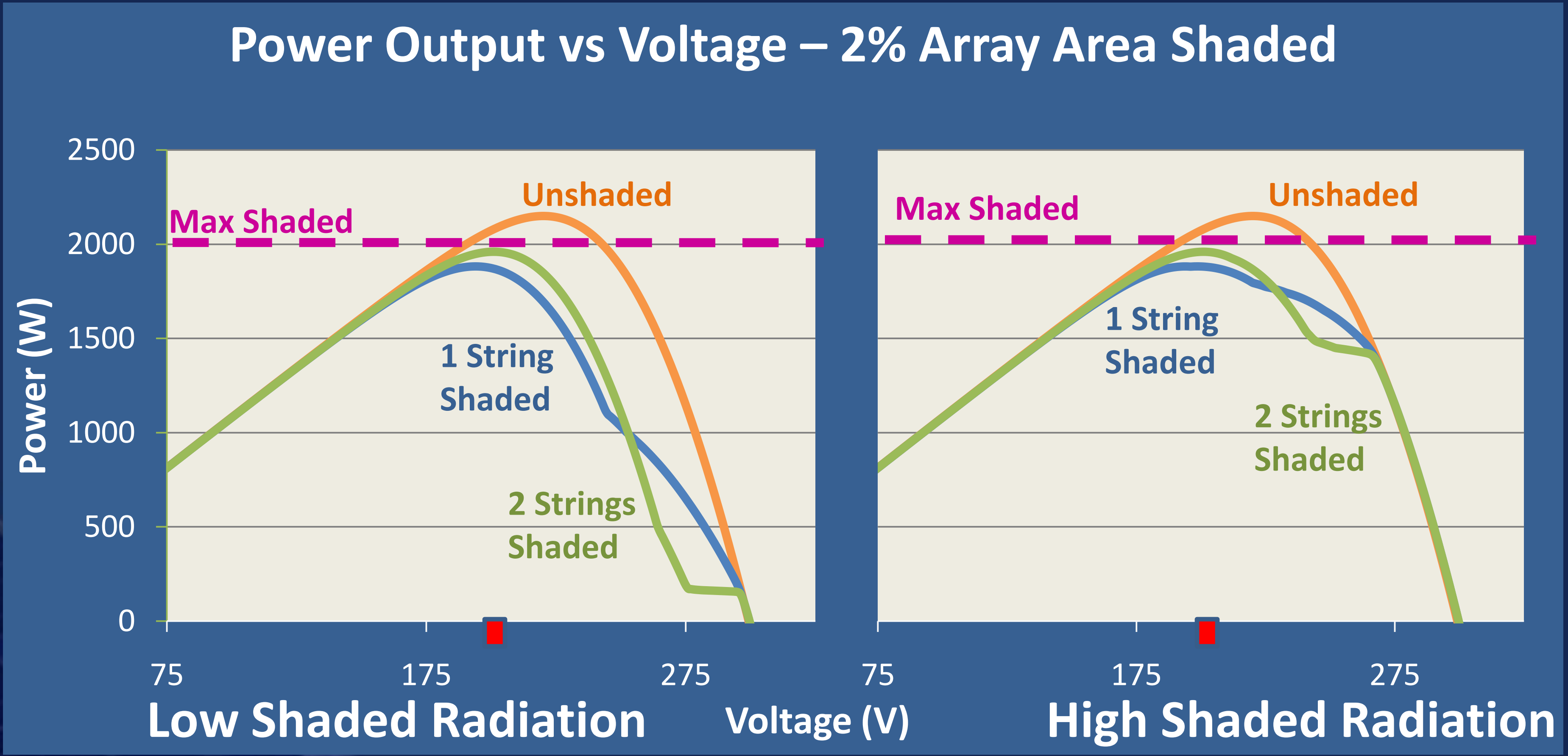
Parallel String Shading Distribution



Isolated Shading – One string in array is shaded

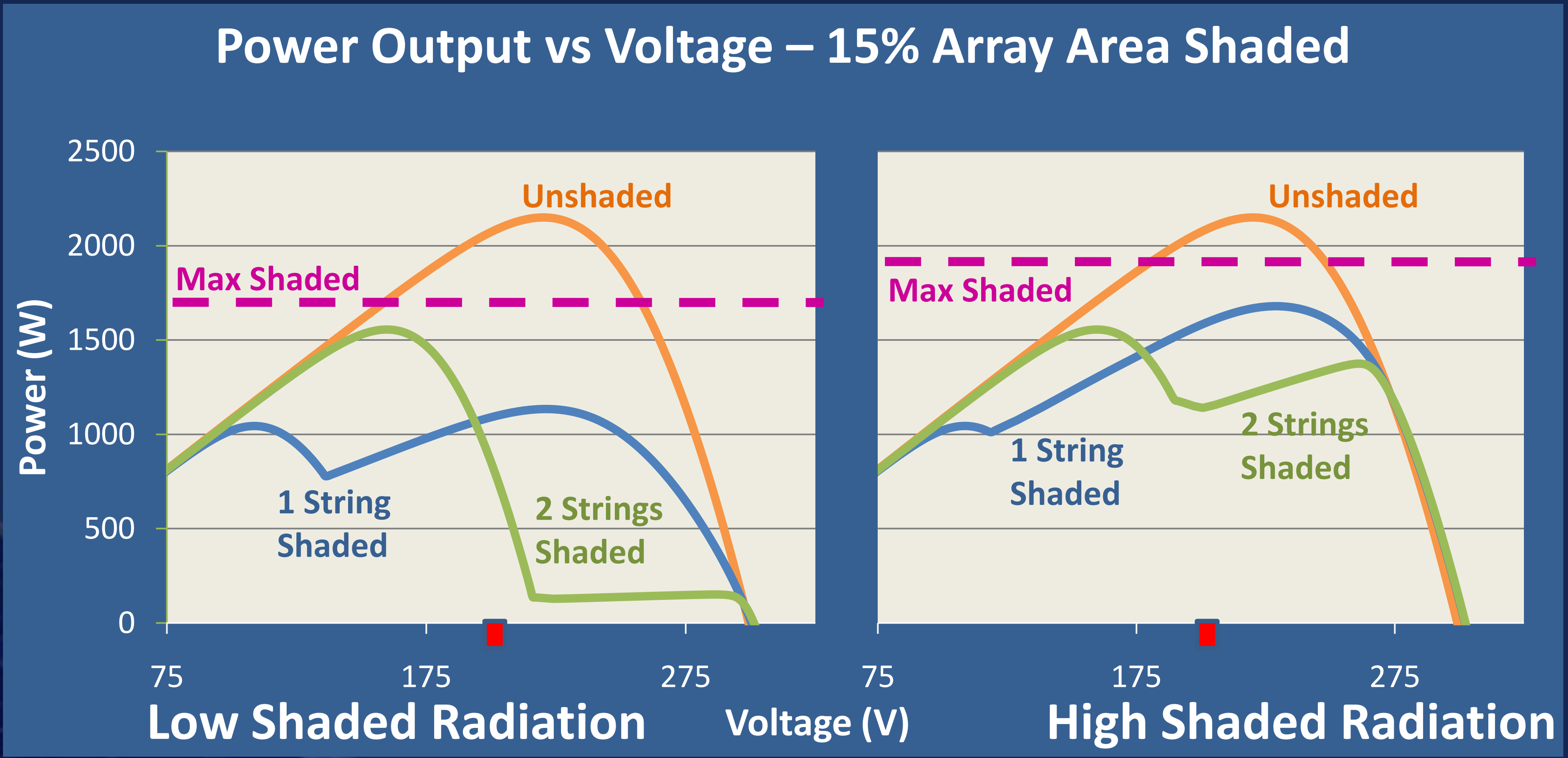
Distributed Shading – Both strings in array are shaded

Partially Shaded Parallel String Performance (small shading obstacle)



- Low shaded radiation = 5% of unshaded; high shaded radiation = 50%
- Distributed shading outperforms isolated
- Limited power recovery potential with per-panel MPPT (“Max Shaded”)

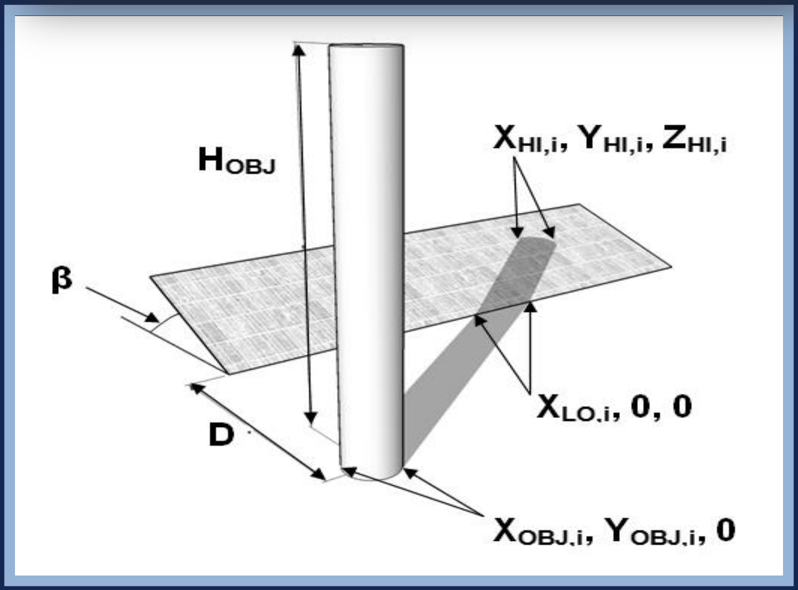
Partially Shaded Parallel String Performance (Large Shading Obstacle)



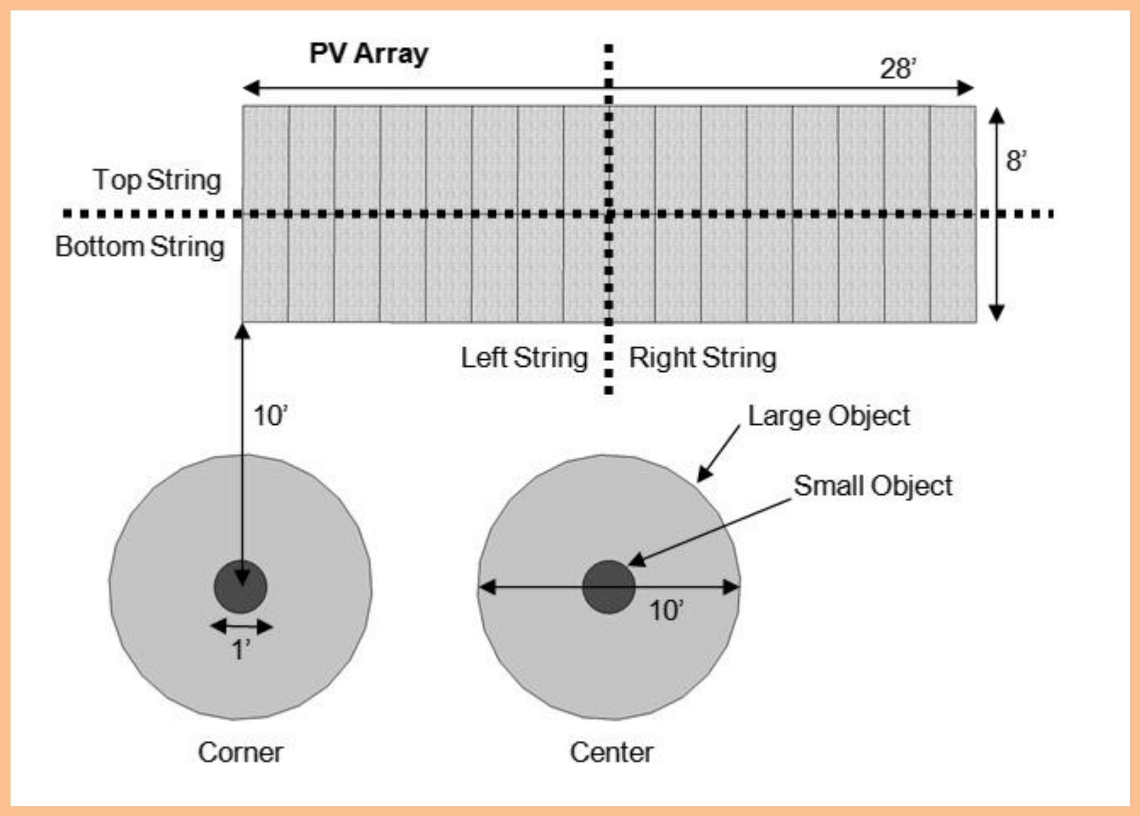
- Low shaded radiation = 5% of unshaded; high shaded radiation = 50%
- Isolated shading outperforms distributed
- High power recovery potential with per-panel MPPT ("Max Shaded")

SHADING OBSTACLES

- Opaque, cylindrical objects
- Shadow mapped onto array
- Shading on per-cell basis
- Shaded cells receive diffuse/reflected radiation



SIMULATED CASES



- 2.7kW south facing BIPV array with roof pitch tilt in Boulder, CO
- 2 parallel string divisions
- Obstacles have 1' and 10' diameter
- Corner or center placement
- **8 total cases**

Annual Shade Loss

Conventional Array -- Small Obstacle

Object Position	String Division	% of Hrs. Shaded	Avg % Cells Shaded	% Hrs. MPP Outside Inverter Range	% System Output Loss From Shading
Corner	Left-Right	37%	2%	9%	6%
	Top-Bot	37%	2%	5%	4%
Center	Left-Right	65%	1.5%	14%	8%
	Top-Bot	65%	1.5%	4%	5%

- Disproportionate losses based on fraction of area shaded
- Inverter input voltage range affects shading loss
- Greater annual losses when array shading isolated to one string
- **Losses very dependent on array configuration!**

IMPACT OF DMPPT
SMALL OBSTACLE

Object Position	String Division	% Shading Loss with Prototype Converters	Shaded System %Output Difference -- Prototype Converters vs None	Shaded System Max Potential %Output Difference -- Modular vs Central MPPT
Corner	Left-Right	8%	-2%	4%
	Top-Bot	8%	-4%	2%
Center	Left-Right	9%	-1%	5%
	Top-Bot	9%	-4%	2%

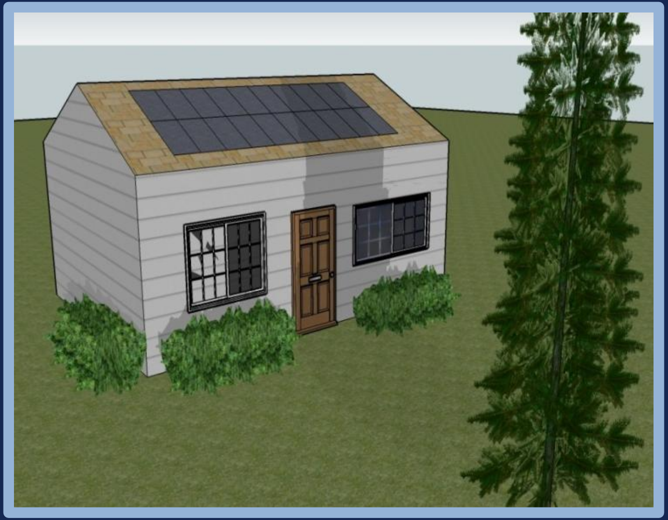
- System shading loss with DMPPT independent of array string division
- Small fraction of power is recoverable using ideal modular power point tracking , so converter power gains outweighed by efficiency and insertion losses of prototype unit
- **Recoverable power/energy fraction highly dependent on array configuration!**

Annual Shade Loss

Conventional Array -- Large Obstacle

Object Position	String Division	% of Hrs. Shaded	Avg % Cells Shaded	% Hrs. MPP Outside Inverter Range	% System Output Loss From Shading
Corner	Left-Right	62%	11%	9%	18%
	Top-Bot	62%	11%	11%	22%
Center	Left-Right	86%	11%	17%	28%
	Top-Bot	86%	11%	22%	40%

- Disproportionate losses based on fraction of area shaded
- Inverter input voltage range affects shading loss
- Greater annual losses when array shading distributed between strings
- **Losses very dependent on array configuration!**



IMPACT OF DMPPT

LARGE OBSTACLE

Object Position	String Division	% Shading Loss with Prototype Converters	Shaded System %Output Difference -- Prototype Converters vs None	Shaded System Max Potential %Output Difference -- Modular vs Central MPPT
Corner	Left-Right	15%	3%	8%
	Top-Bot	15%	8%	13%
Center	Left-Right	21%	10%	15%
	Top-Bot	21%	31%	37%

- System shading loss with DMPPT independent of array string division
- Significant fraction of power lost is recoverable using modular power point tracking, so there are substantial converter power gains despite efficiency and insertion losses of prototype unit
- **Recoverable power/energy fraction highly dependent on array configuration!**

Modeling and Shade Impact Factor (SIF)

- Shade Impact Factor (SIF) is relation between area of array shaded and power lost due to shading

$$SIF = \frac{\text{\% Power Loss From Shade}}{\text{\% Array Shaded}}$$

- Calculated assuming shaded portions receive either (i) no radiation or ii) the diffuse/reflected radiation
- Calculated with array fraction shaded in terms of cells (area) or substrings (bypass diode groups)
- Method:
  - Hourly calculate % array shaded
  - Apply resulting derate to hourly unshaded power produced
  - Calculate annual derated sum and compare to shaded cell-by-cell model total, adjusting weighting until correct SIF is found

Annual Calculations of SIFs for Conventional vs DMPPT Systems

$$SIF_{CONV} = \frac{\%\ \text{Power Loss From Shade}}{\%\ \text{Area or Substrings Shaded}}$$

$$SIF_{DMPPT} = \frac{\%\ \text{Power Loss From Shade}}{\%\ \text{Area or Substrings Shaded} * \frac{\text{Diffuse Rad}}{\text{Total Rad}}}$$

Object Size	Array Division	SIF
Small	Area	3.2 - 5.3
	Substrings	1.1 - 1.7
Large	Area	1.6 - 2.4
	Substrings	1.3 - 1.9

Object Size	Array Division	SIF
Small	Area	2.7 - 2.9
	Substrings	$\boxed{0.9 - 1}$
Large	Area	1.2 - 1.3
	Substrings	$\boxed{0.9 - 1}$

Conclusions

- Power recovery potential depends on shading severity, array configuration, inverter voltage range, and panel electrical characteristics
- DMPPT power converters significantly increase annual energy capture potential in arrays with moderate shading, especially for shading distributed across multiple strings
- No “one size fits all” SIF to quantify shading losses in conventional systems
- Preliminary results indicate potential for SIF to be used to accurately model DMPPT; most promising when implemented at bypass diode substring level accounting for radiation received by shaded substrings

Acknowledgements

Thanks to the NSF for their sponsorship of this work

Questions?

MIC Operation

- **Buck mode**:

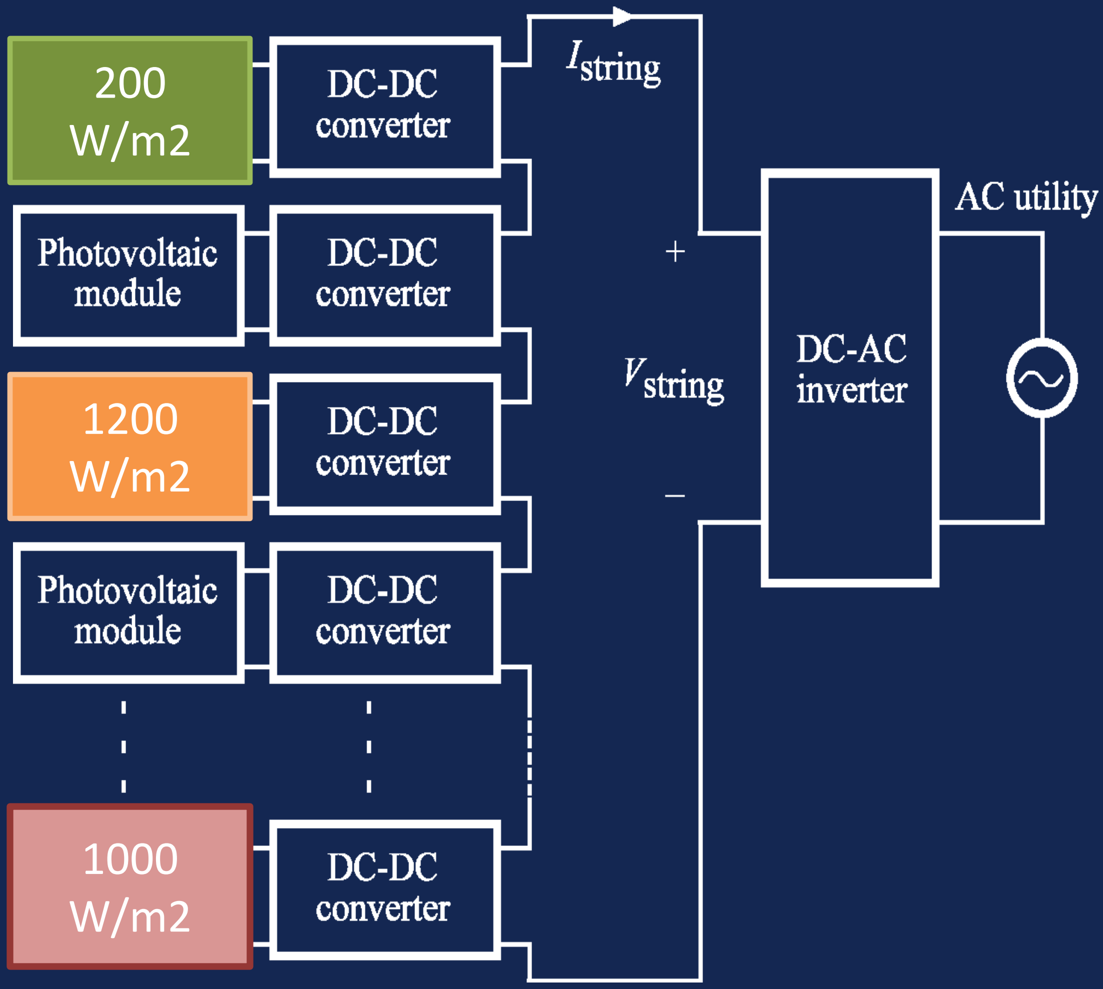
  $I_{mod} < I_{string}$. Converter decreases module V_{out}, while increasing I_{mod} to I_{string}

- **Boost mode**:

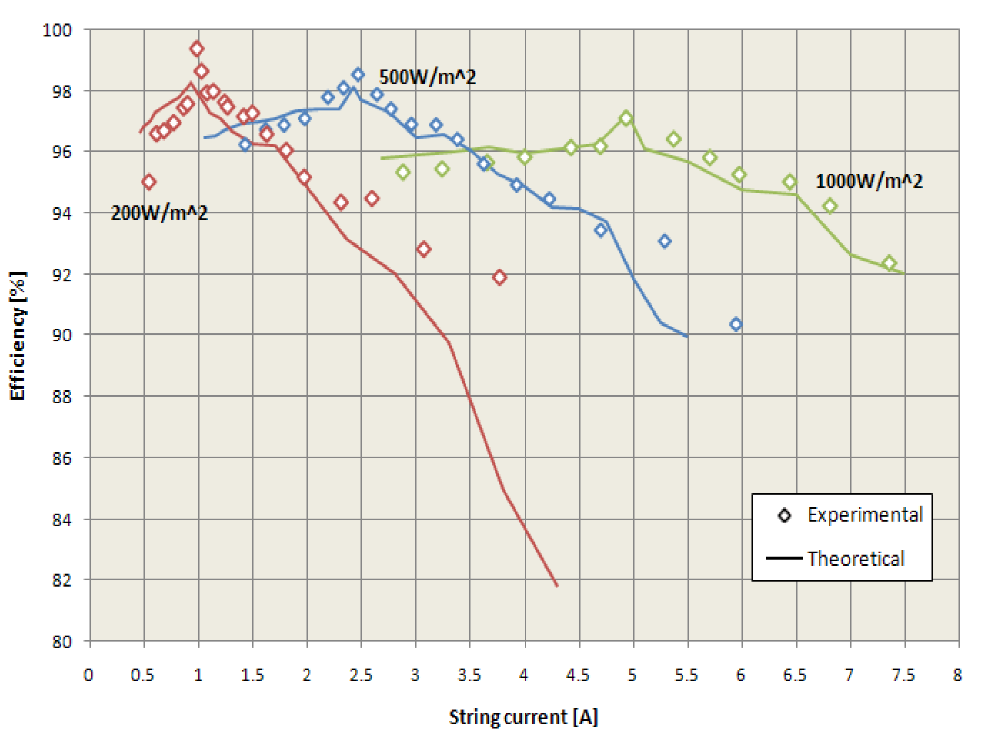
  $I_{mod} > I_{string}$. Converter increases module V_{out} while decreasing I_{mod} to I_{string}

- **Pass-through mode**:

  $I_{mod} = I_{string}$. Converter input directly connected to output (most efficient)



Experimental Validation



MIC Power Stage Efficiency Verification

Efficiency typically above 95% during normal operation

Numbers do not include "housekeeping" insertion loss of 0.5-0.8W

Simulation results within 5% tolerance of experimental data

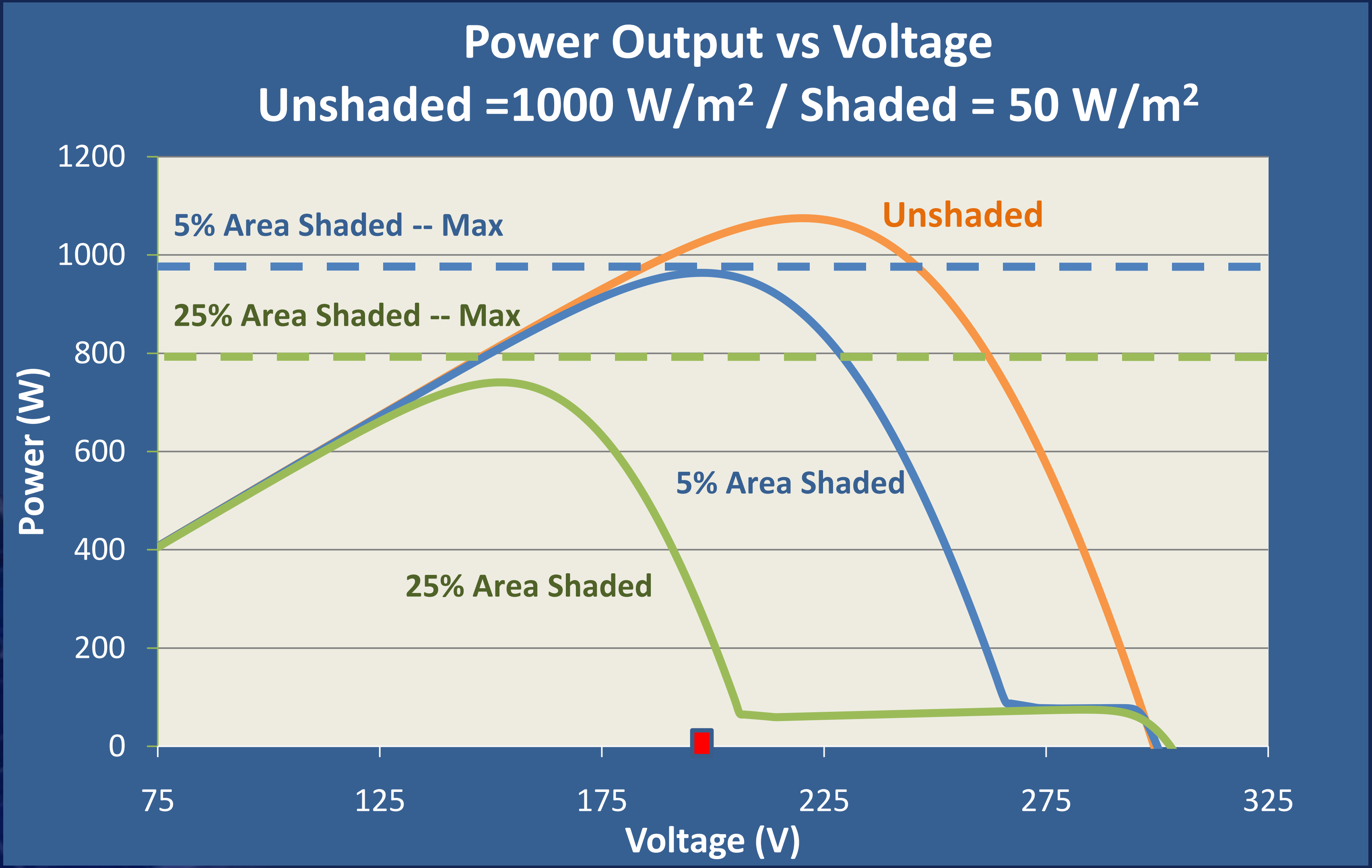
Simulation Performance Verification

Output Power for a 3-Module String With and Without MICs

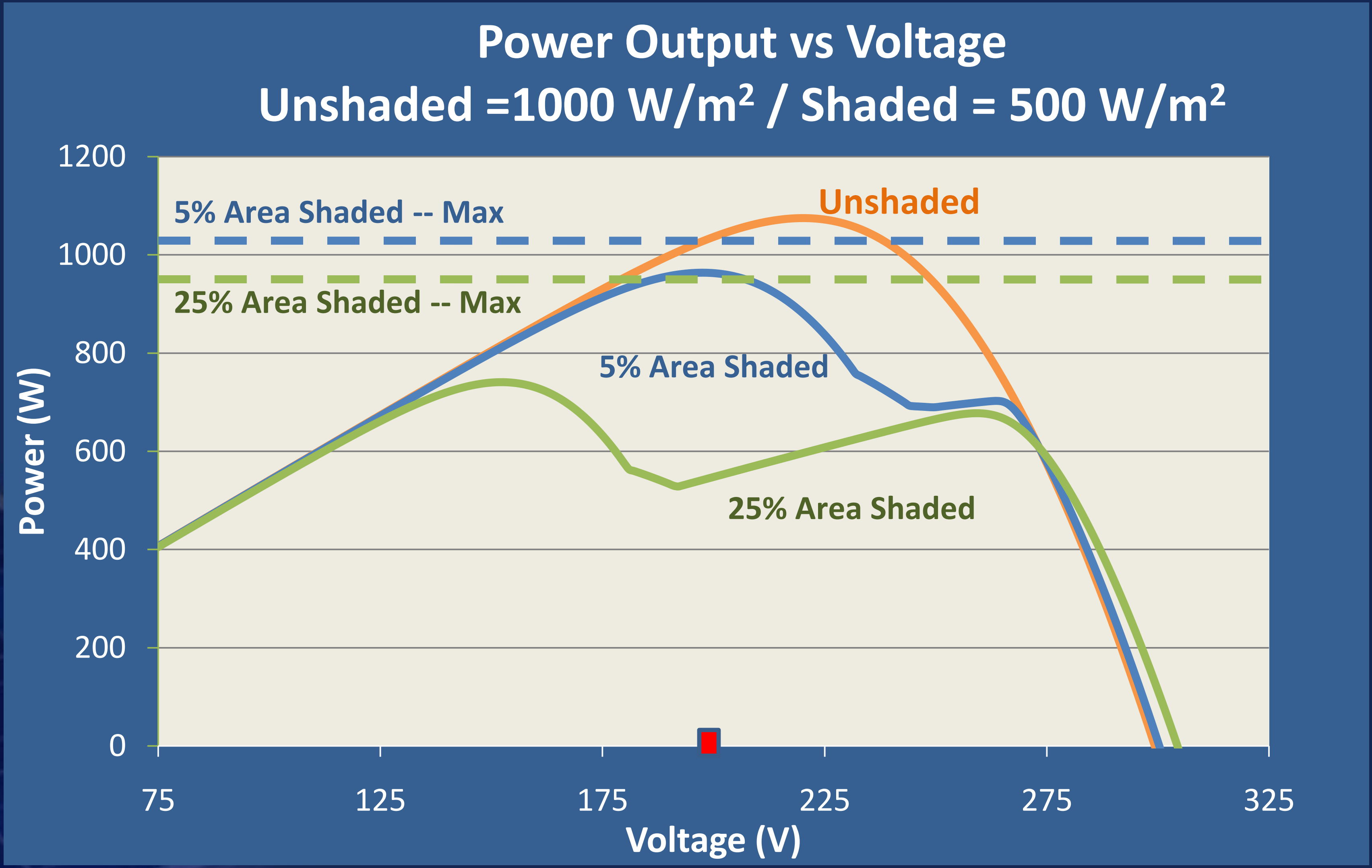
	turned panels	Output power*	
		Experimental	Simulation
Series string	0	100%	103%
	1	67%	68%
	2	39%	36%
Series string with MICs	0	96%	99%
	1	79%	83%
	2	54%	59%

*Percentage of ***experimental*** output power of a 3-module string at 1100 W/m^2 and 45^{o}C

Partially Shaded Series String Performance (Low Diffuse Fraction)



Partially Shaded Series String Performance (high diffuse fraction)



What if I just use SIF=1?

Shaded Receives No Radiation

Array Fraction	DMPPT?	Misprediction
Area	NO	3% - 38%
	YES	0% - 2%
Sub Strings	NO	0% - 30%
	YES	-5% - -1%

Shaded Receives Diffuse Radiation

Array Fraction	DMPPT?	Misprediction
Area	NO	4% - 43%
	YES	2% - 4%
Sub Strings	NO	1% - 37%
	YES	-0.5% - 0.5%